

6. Calibration Procedures and Computer Automation

6.1 Spectral Responsivity

This section describes the spectral responsivity measurement procedures for both the UV SCF and Vis/NIR SCF. These correspond to Service ID numbers 39071S through 39075S. The primary difference between the operation of the two SCFs is that the UV SCF can accommodate only one test detector per responsivity measurement run, and the Vis/NIR SCF is set up for two test detectors. The spatial uniformity of the responsivity for new photodiodes, which is included in 39071S and 39073S, is also measured as described in section 6.2.

6.1.1 Calibration Procedures

New photodiodes are visually inspected for defects and placed in one of the specially designed fixtures described later in section 9.5. Each photodiode has a serial number engraved on the fixture. The photodiode dynamic impedance (shunt resistance) is measured with an HP 4145A I-V plotter to confirm the manufacturer's specification. The shunt resistance of the photodiode needs to be 1000 times greater than the input impedance of the transimpedance amplifier for it not to deviate from linear operation. Typically, an amplifier gain of 10^6 is used, requiring that the photodiode shunt resistance must be greater than 10 k Ω . If needed, the diode window is cleaned with lens tissue and spectral-grade acetone before any optical measurements are made. Ethanol has also been used by others to clean photodiodes and optical windows [44].

The spectral responsivity is measured by direct comparison to two working standards using the "substitution method with monitor" described in section 3.2. The two working standards are selected from a randomly generated weekly schedule. The test detector(s) and working standard detectors are aligned perpendicular to the optical axis by using the He-Ne laser as the monochromator source and retroreflecting the He-Ne beam back onto itself. The appropriate broadband source used for the measurement is chosen and the detector positioned at the focal plane of the SCF exit optics. An automated computer routine centers the active area of each detector on the optical axis.

The typical comparison measurement consists of scanning the monochromator through the desired spectral range at wavelength intervals of 5 nm for each detector. This spectral scanning process is repeated three times. The test detector(s) and Vis WS are operated unbiased (the photovoltaic or short-circuit mode) and the signals are measured with calibrated transimpedance amplifiers and DVMs. Figure 4.2 shows that the optical power used for these measurements is typically less than 1 μ W. The test to monitor (eq (3.23)) and working standard to monitor (eq (3.24)) ratio data are stored on the computer for later analysis to determine the spectral responsivity. The standard deviation of the test (or working standard) and monitor detector ratios is less than either individual signal standard deviation. This is the result of simultaneously sampling both the test (or working standard) and monitor detector. Examples of the typical signals from a Hamamatsu S1337 and the monitor photodiode are shown in figure 6.1. Also, shown are the signal ratios and the relative standard deviations of each signal and ratio. Figure 6.1 shows the ratio relative standard deviation is lower than either individual signal standard deviation.

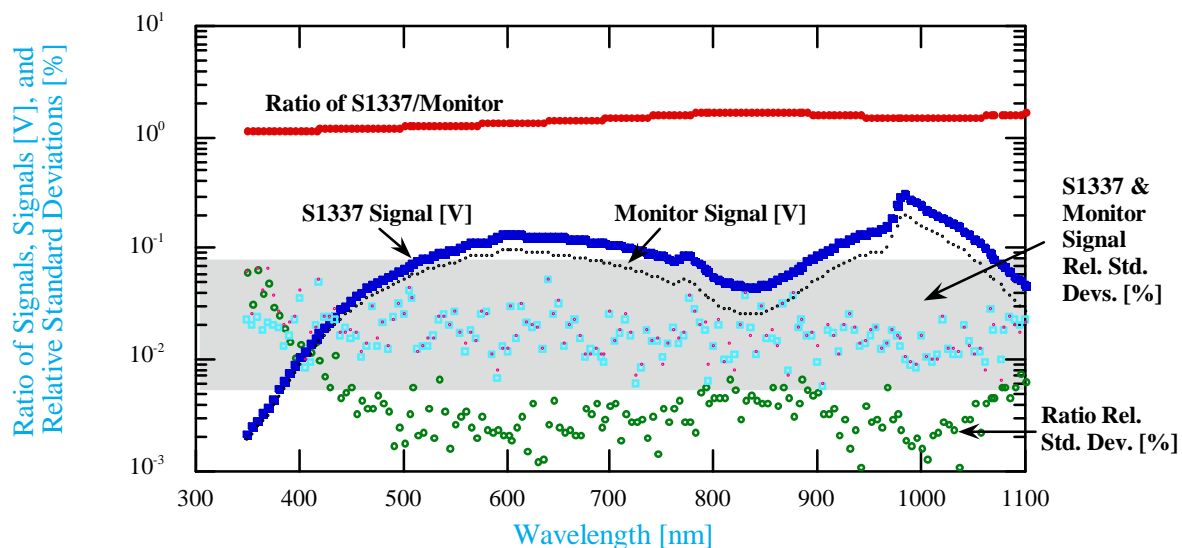


Figure 6.1. Typical signals from Hamamatsu S1337 and monitor photodiodes. The S1337 and monitor signals are shown as closed squares and triangles, respectively. Also shown are the signal ratios as closed circles. All curves are the means of 10 samples. The relative standard deviations of the S1337 and monitor signals are shown respectively as open squares and triangles in the shaded area. The relative standard deviations of the ratios are shown as open circles and for measurements above 400 nm are lower than the individual signal standard deviations. Note: The S1337 and monitor signal standard deviation curves are nearly indistinguishable because the source noise rather than detector noise dominates the measurement.

The laboratory environment (temperature, humidity, etc.) is monitored and recorded at the start of each scan although this data is not used to correct the measurement results. The temperature of specially designed detectors that have temperature sensors built into their housings can also be recorded. The average temperature during the measurements is then reported.

The spectral responsivity is determined by using eq (3.27) for each test and working standard detector spectral scan combination. The reported spectral responsivity of the test detector is the weighted mean [40] of all the scans with both working standard detectors. Examples of typical photodiode spectral responsivities are shown in figure 6.2.

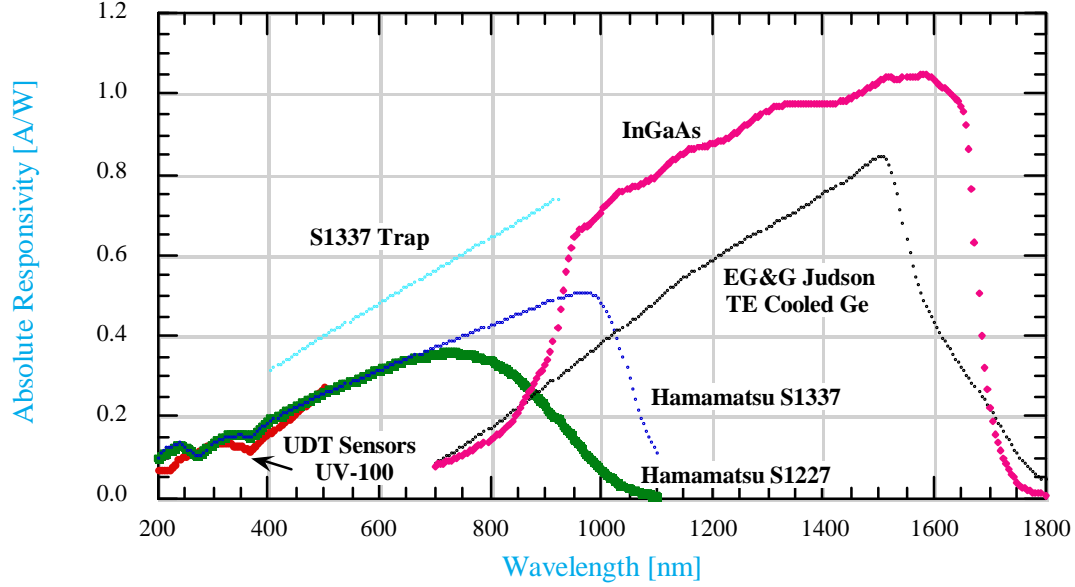


Figure 6.2. Spectral responsivities of typical Si, InGaAs, and Ge photodiodes.

6.1.2 Quantum Efficiency

The quantum efficiency is the photon-to-electron conversion efficiency of a photoelectric detector. The quantum efficiency of a detector is often required for particular applications. There is a simple calculation to convert spectral responsivity [$\text{A}\cdot\text{W}^{-1}$] to external quantum efficiency. The external quantum efficiency EQE is given by [10]

$$EQE(I) = \frac{I(I) \cdot h \cdot c}{F(I) \cdot n \cdot e \cdot I}, \quad (6.1)$$

where I is the photocurrent (output current minus the dark output), h is Planck's constant, c is the velocity of light, F is the input radiant flux (power), n is the index of refraction of air, e is the elementary electronic charge, and I is the spectral wavelength. Substituting for the constants h , c , n , and e gives

$$EQE(I) = 1239.85 \cdot \frac{I(I)}{F(I) \cdot I} = 1239.85 \cdot \frac{S(I)}{I}, \quad (6.2)$$

where $S(I) = I(I)/F(I)$ is the spectral responsivity [$\text{A}\cdot\text{W}^{-1}$], and for convenience, I is in nm. Examples of typical photodiode EQEs are shown in figure 6.3.

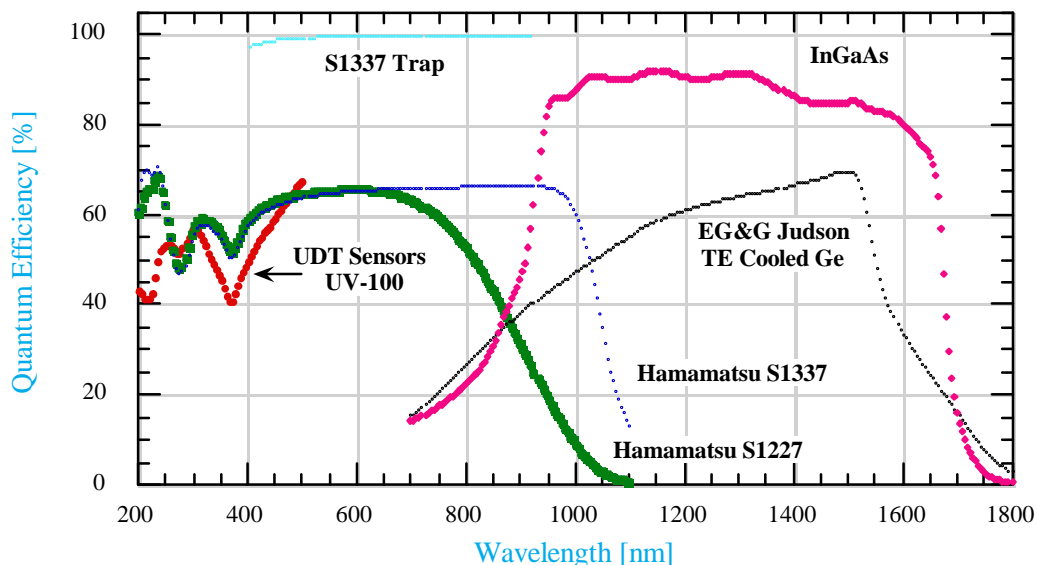


Figure 6.3. Quantum efficiencies of typical Si, InGaAs, and Ge photodiodes.

6.2 Spatial Uniformity

This section describes the procedures used in NIST Service ID numbers 39071S, 39073S, and 39081S to determine the responsivity spatial uniformity of detectors. The spatial uniformity measurement procedures are the same for both the UV SCF and Vis/NIR SCF. The major difference between the two is the beam size. The UV SCF beam diameter is 1.5 mm and the Vis/NIR SCF beam diameter is 1.1 mm. Also, only one detector can be measured at a time in the UV SCF while up to four detectors can be measured in the Vis/NIR SCF.

The spatial uniformity is measured at 350 nm for the UDT Sensors UV100 photodiodes (39071S). The spatial uniformity for the Hamamatsu S1337-1010BQ and, more recently, the Hamamatsu S2281 photodiodes is measured at 500 nm (39073S). UV100 photodiodes are not issued if the responsivity nonuniformity (i.e., slope) is greater than 1 % over the active area or greater than 0.5 % within the center 50 % of the active area or if a discontinuity (a peak or valley) in the responsivity greater than 0.5 % is found within the center 90 % of the active area. Hamamatsu S1337-1010BQ and S2281 photodiodes are not issued if the nonuniformity is greater than 0.5 % over the active area or greater than 0.25 % within the center 50 % of the active area or if a discontinuity greater than 0.25 % is found within the center 90 % of the active area.

In the early 1990's, it was found that many silicon photodiodes have a significant change in the uniformity as a function of wavelength, particularly as the wavelength approached the bandgap (1100 nm). Nonuniformity is due to inhomogeneity in the photodiode material - typically inhomogeneity in surface recombination centers at shorter wavelengths [45, 46] and bulk recombination centers at longer wavelengths [47]. The nonuniformity near the bandgap has also been related to the (non)uniformity of the bonding material's reflectance [48]. Because the semiconductor is almost transparent near the bandgap, changes in the spatial reflectivity of the bonding material affect the amount of light reflected and therefore the responsivity of the photodiode.

Since 1993, the uniformity of the S1337-1010BQ and the S2281 diodes are also measured at 1000 nm [49]. Photodiodes are not issued if the nonuniformity is greater than 1 % over the active area or greater than 0.5 % within the center 50 % of the active area. Also, if a discontinuity greater than 0.5 % is found within the center 90 % of the active area.

S1337-1010BQ photodiodes with a significant change in uniformity between 500 nm and 1000 nm are seen less frequently in recently manufactured diodes. Diodes issued by NIST prior to the discovery of this effect in 1993 were not measured at 1000 nm. When these diodes are resubmitted for measurement (39074S), the uniformity is checked at 1000 nm; and the customer is notified if a significant nonuniformity is found.

6.2.1 Measurement Method and Calibration Procedure

The detectors are aligned as described above in section 6.1. The typical measurement consists of setting the monochromator to the desired wavelength and, for a 1 cm² test detector, scanning a 12 mm x 12 mm area in 0.5 mm steps. The test detector is operated unbiased (the photovoltaic or short-circuit mode); and the signal is measured with a calibrated transimpedance amplifier and a DVM. The typical amplifier gain for the test detector is 10⁶. Figure 4.2 shows the optical power used for these measurements is typically less than 1 μW. The test to monitor (eq (3.23)) ratio data is stored on the computer for later analysis.

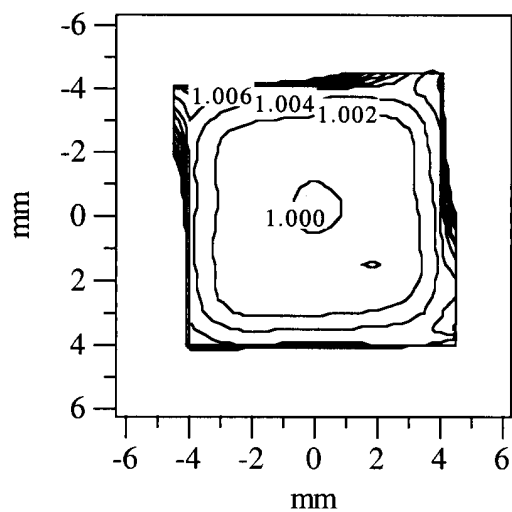
The scans are always in the same horizontal direction; and the vertical direction is reversed in a “raster” scan, starting in the upper left corner moving to the lower right corner of the photodiode. The scan is large enough for the beam to move completely off of the active area (or onto an aperture). Scanning horizontally in only one direction puts the stage drive against the same side of the drive screw. For the vertical, gravity keeps the stage always against the same side of the screw. This reduces hysteresis in the movement of the stages.

The laboratory environment (temperature, humidity, etc.) is monitored and recorded at the beginning and end of each scan, although this data is not used to correct the measurement results. The temperature of specially designed detectors that have temperature sensors built into their housings can also be recorded. The average temperature during the measurements is then reported.

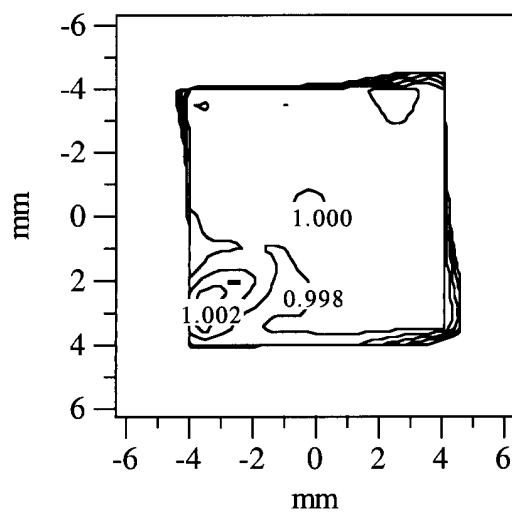
The test to monitor detector ratios are normalized to the mean of the center ratios. The reported spatial uniformity figure is constructed from these normalized ratios. Figure 6.4 shows the spatial uniformities of the central portion of typical Hamamatsu S1337-1010BQ and S2281 photodiodes at 500 nm and 1000 nm. Similar spatial uniformity scans are shown in figure 6.5a for UV100 and figure 6.5b, c, and d for Judson EG&G thermoelectrically cooled Ge photodiodes.

6.2.2 Limitations

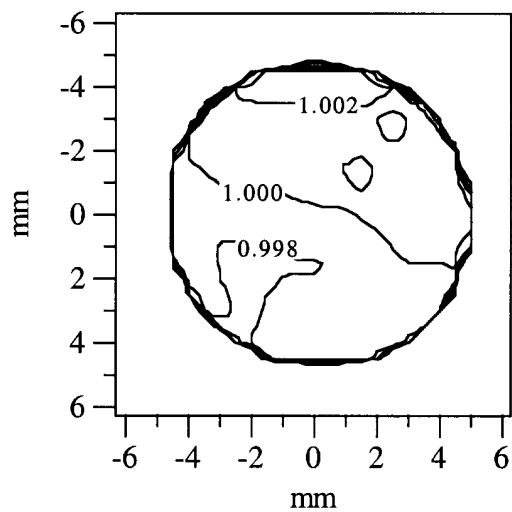
The size of the active area to be measured has to be significantly larger than the beam size since the beam is “clipped” (or vignetted) at the edges of the active area or aperture in front of the detector. Also the spatial shape of the optical beam is assumed constant during the measurement.



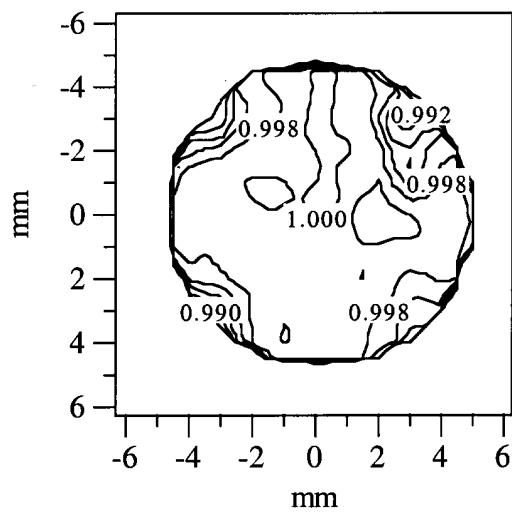
(a) Hamamatsu S1337 at 500 nm.



(b) Hamamatsu S1337 at 1000 nm.

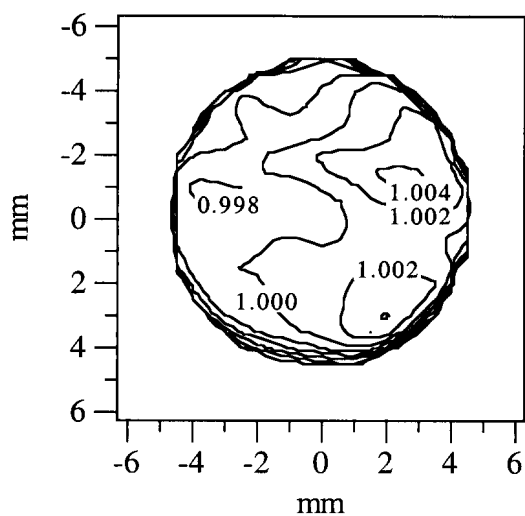


(c) Hamamatsu S2281 at 500 nm.

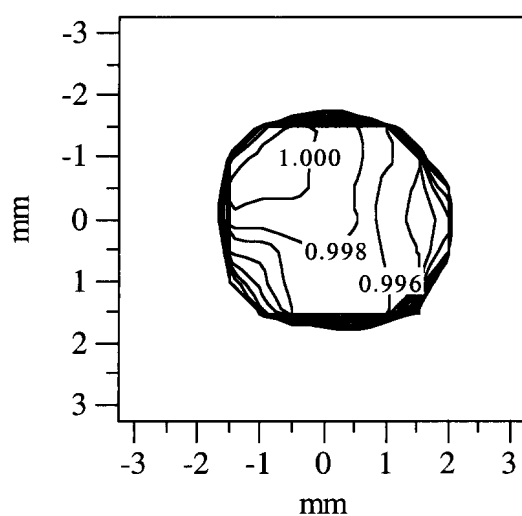


(d) Hamamatsu S2281 at 1000 nm.

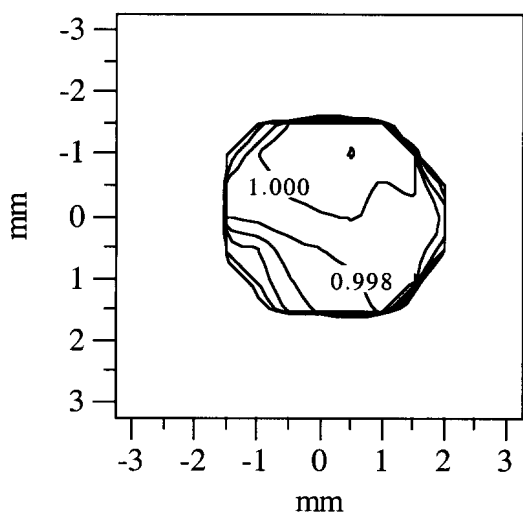
Figure 6.4. Spatial uniformities of typical Hamamatsu S1337 and S2281 photodiodes. The responsivities are normalized to the center values.



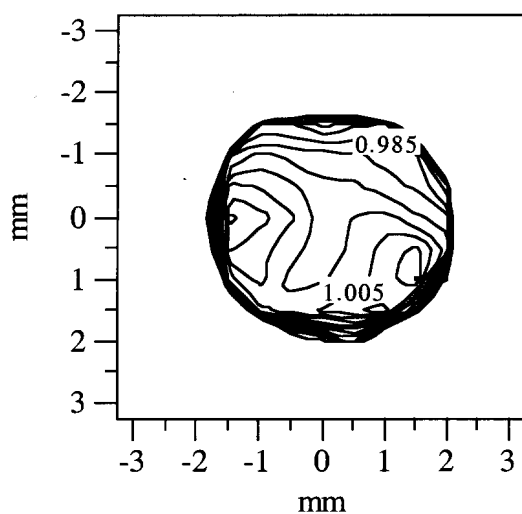
(a) UDT Sensors UV100 at 350 nm.



(b) EG&G Judson TE Ge at 1000 nm.



(c) EG&G Judson TE Ge at 1500 nm.



(d) EG&G Judson TE Ge at 1600 nm.

Figure 6.5. Spatial uniformities of typical UDT Sensors UV100 and EG&G Judson Ge photodiodes. The responsivities are normalized to the center values.

6.3 Computer Automation

This section describes the computer automation of the UV and Vis/NIR comparator facilities. The automated equipment and computer software used for typical measurements are briefly described. Automating the equipment (which sometimes requires modification) and writing, testing, and documenting the software is a major undertaking. The operation of the facilities would not be practical without this high degree of computer automation.

6.3.1 Computer Automated Equipment

Block diagrams that include current and future computer controlled equipment for the Vis/NIR SCF and UV SCF are shown in figures 6.6 and 6.7, respectively. All of the equipment is controlled by one computer via an IEEE-488 (GPIB) bus. This computer stores all of the data and the analyzed responsivity files. A Local Area Network (LAN) connects this computer with several others which are used for further data comparisons and writing test reports; allowing the SCF control computer to be dedicated to taking measurements. Weekly backups of the data files are sent to a second computer.

Several key components of the SCFs are controlled by commercial servo motor controllers: the horizontal and vertical (x,y) translation stages, source section, and the rotary stage in the UV SCF. The wavelength drive of the Cary-14 monochromator used with the Vis/NIR SCF was modified and is also driven by a computer controlled servo motor.

All of the DVMs, lock-in amplifiers, and multiplexers are computer controlled. A digital I/O module addressed over the IEEE-488 bus signals the shutter controllers to open or close. A commercial laboratory environmental monitor records the laboratory and enclosure temperatures, the humidity and barometric pressure, and the electrical power line voltage and frequency. Some detectors have temperature monitoring circuitry that produces a voltage signal proportional to their temperature. These signals can also be multiplexed via computer control to the DVM.

In the future the TE temperature controllers and transimpedance amplifiers will also be controlled via IEEE-488 bus and computer. The Vis/NIR SCF wavelength encoder and display will be upgraded, allowing communication with the controlling computer. A new monochromator will soon be incorporated in UV SCF which will have computer selectable order sorting filters.

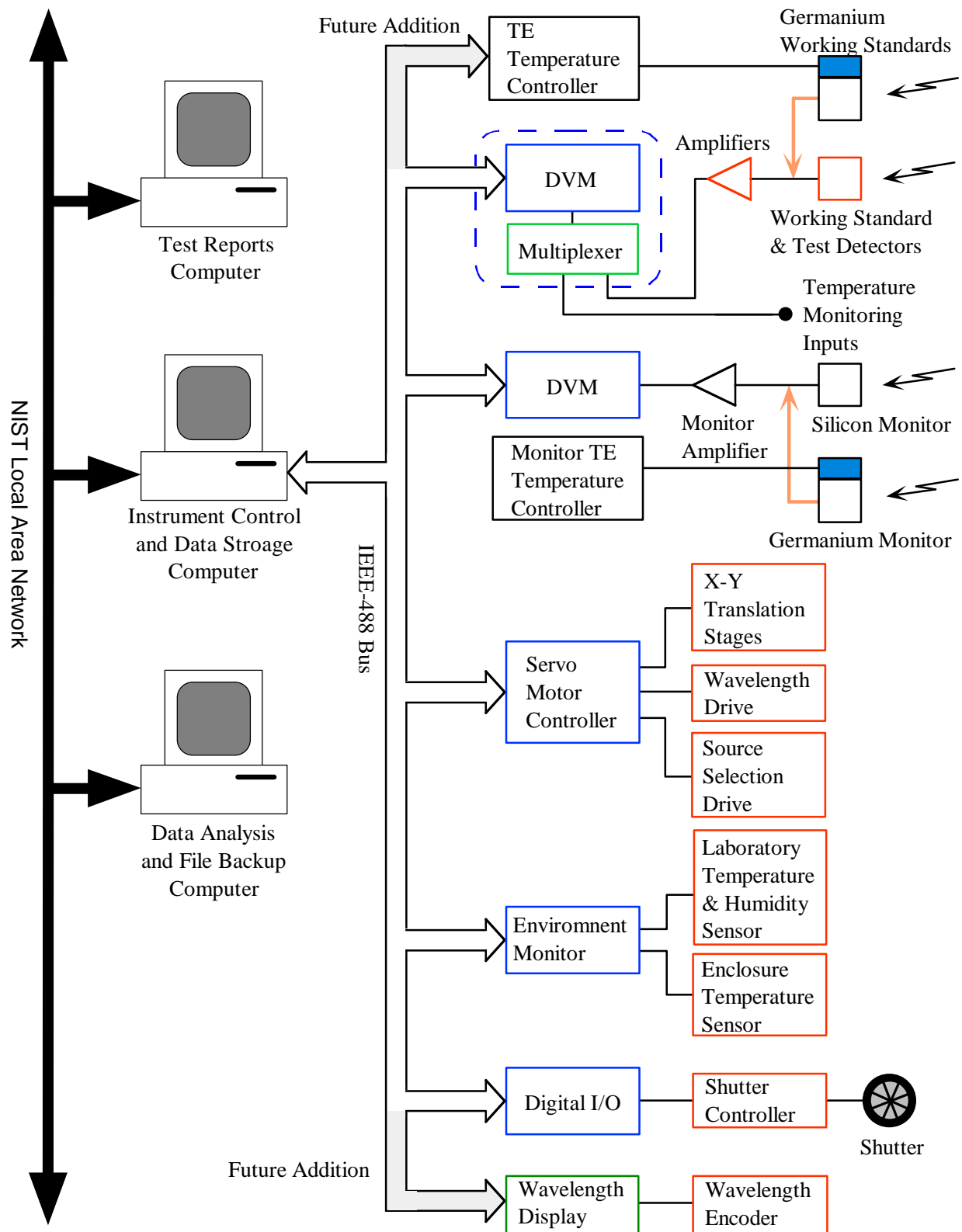


Figure 6.6. Vis/NIR SCF computer control block diagram.

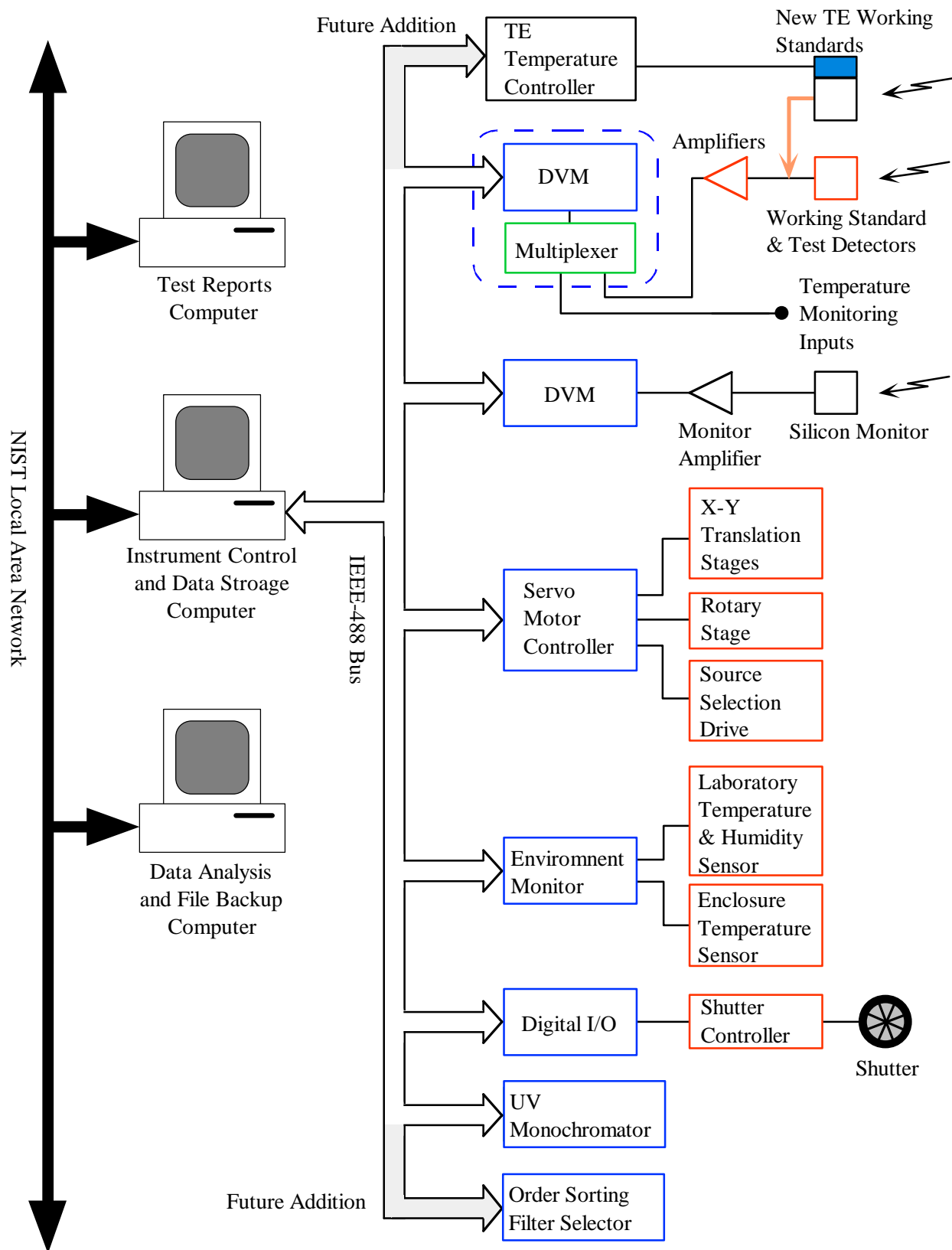


Figure 6.7. UV SCF computer control block diagram.

6.3.2 Computer Calibration Programs

SCF Setup Program

This program performs three functions: initialize the SCF instruments, align the test and working standard detectors, and verify the signal levels from the detectors before starting measurements. The operator uses this program interactively (via the front panel controls and translation stage joystick) to align a new detector placed in the SCF. This program updates a file that contains the detector names and translation stage (x,y) positions for use later by other computer programs.

Spectral Scanning Program

This program takes data from one to four detectors (test and working standard detectors), stores the data on hard disk, and prints the results. The analysis program can be set to automatically run when the measurements finish. The operator sets several detector parameters such as the time constant and amplifier gain, whether to use a detector (position), and whether the detector is a working standard. Other operator inputs are the spectral range start and stop wavelengths, spectral step size, number of samples at each wavelength, number of (repeat) scans for the measurement, and which SCF source to use. The operator can also input specific comments about the measurement.

After the parameters have been entered, the program positions the first detector into the beam and starts taking data (see fig. 6.8). The program determines the test (measurement) number and creates unique filenames for each detector using this number and the detector's name entered in the SCF setup program. The program updates the computer screen with the current scan number, the detector name and position for the detector currently being measured, filename, and the pathname to the data stored on the hard disk. The program also graphs the test detector to monitor ratio (eq (3.23)), the working standard detector to monitor ratio (eq (3.24)), and the percent standard deviation of the ratios. The program saves the "raw" ratio data files on the hard disk after each detector spectral scan. After completion of the measurement, a record is printed of the operator inputs, graph of the detector to monitor ratios, and graph of the percent standard deviation of the ratios.

The "raw" ratio data files are two dimensional ASCII text arrays that are tab delimited and consist of "header" lines and data lines. The "header" lines contain information about the measurement parameters, laboratory environment (e.g., temperature), and detector temperature (if provided) or auxiliary thermistor reading. The data columns are: (1) wavelength, (2) mean ratio of the (test or working standard) detector signal to the monitor signal, (3) the percent standard deviation of those ratios, (4) mean detector signal, (5) detector percent standard deviation, (6) mean monitor signal, and (7) monitor signal percent standard deviation. (See fig. 6.1.) If more than one scan is taken then the environmental and detector temperature information and additional data are added at the end of the data file after each scan. If selected by the operator, the spectral responsivity calculation program is automatically executed after all the spectral scans have completed.

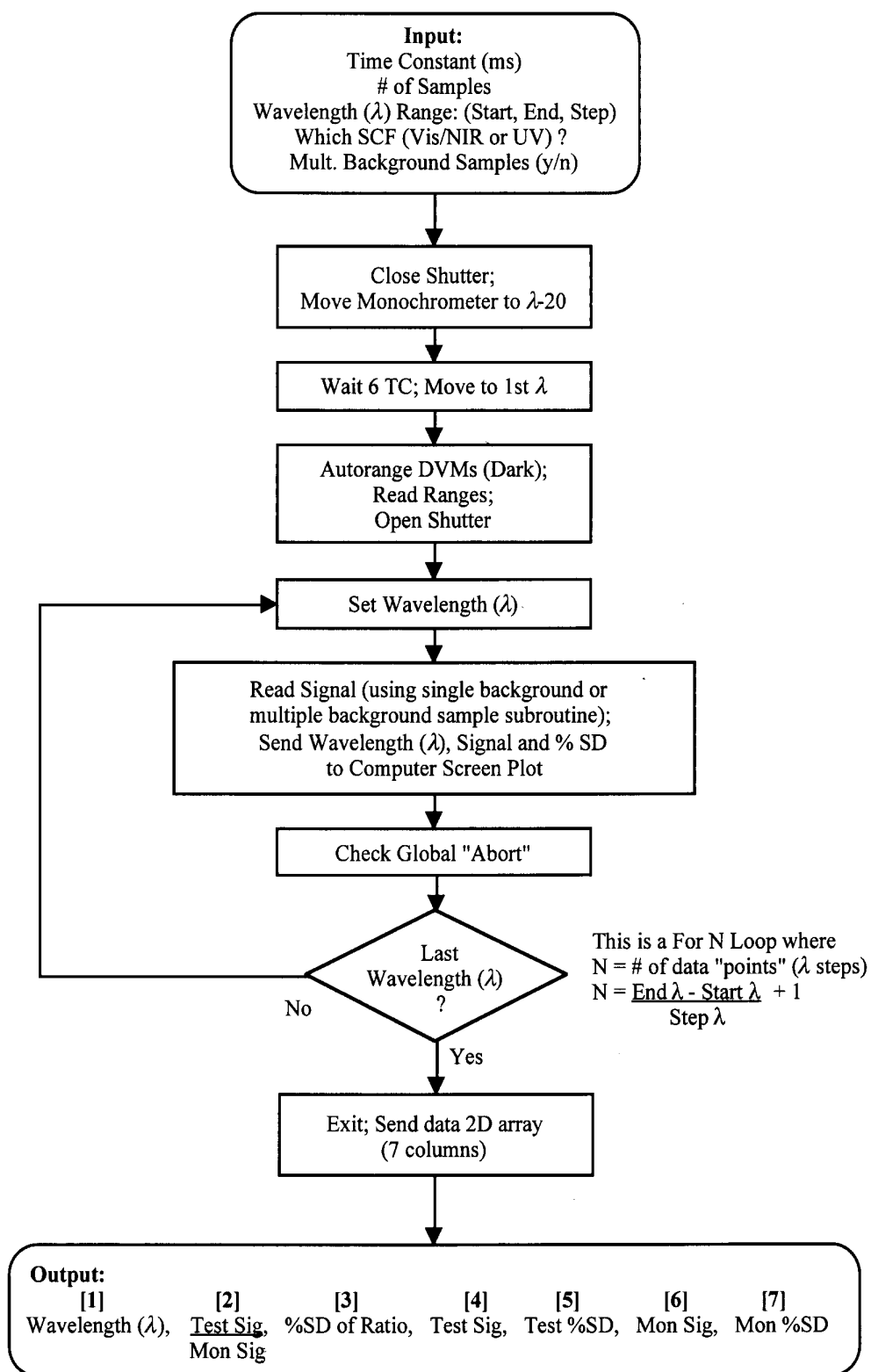


Figure 6.8. Measurement (computer) program flowchart for one detector scan.

Spectral Responsivity Calculation Program

This program calculates the spectral responsivity for the test detector(s), stores the results on the hard disk, and prints the (weighted) mean responsivity and relative measurement uncertainty (graphs), detector filenames, and control settings. The inputs to the program are the test and working standard detector “raw” ratio data filenames, which working standard reference (calibration) data to use, and whether a NIST transimpedance amplifier or other calibrated amplifier was used with the test detector.

The gain range and detector position in the SCF are extracted from the data files for the test and working standard detectors. This is used to select the corrected (calibrated) gain factor for the appropriate NIST amplifier. For detectors with internal amplifiers the gain range is multiplied by the customer supplied amplifier gain correction factor to determine the corrected gain factor. The program next reads and formats the ratio data files and the working standard reference data file. The program determines the responsivity for a test detector by using eq (3.27) for each test and working standard detector spectral scan combination. Then if more than one spectral scan was taken a weighted average of the mean is calculated [40] using the standard deviations from each scan as the weighting factor. The weighted average uncertainty is also calculated.

If the responsivity data is negative (because of reversed polarities on the photodiodes) the responsivity data is inverted, i.e., $-S(I)$. Then the spectral responsivity and relative uncertainty are graphed on the computer monitor. The detector temperature monitor (or auxiliary thermistor) data for all the scans are averaged for each test detector. The output filename is unique and constructed very similar to the “raw” data filename using the test number and test detector name. The responsivity output file is created as a tab delimited ASCII text array. The file consists of “header” lines and data lines. The “header” lines contain information about the test number, detector (name), test date, working standard(s) and reference data, internal amplifier gain and correction factor (if applicable), average detector temperature, and column headings. The data columns are: (1) wavelength, (2) weighted average spectral responsivity, (3) relative uncertainty. After the measurement is complete a record of the operator inputs and graphs of the weighted average spectral responsivity and relative uncertainty are printed.

Spatial Scanning Program

This program spatially scans the SCF beam across the active area of the detector by using the x,y translation stages to translate the detector. The data is stored on hard disk, and the measurement results are printed when the program finishes execution. One detector in the UV SCF and up to four detectors in the Vis/NIR SCF can be measured at one time. The measurements can be programmed to repeat at different wavelengths.

The program inputs are the scan wavelength, number of samples at each data point, detector parameters such as the time constant and amplifier gain, whether to use a detector (position), and operator comments. Also input are the spatial scan horizontal (x) and vertical (y) dimensions and step sizes. The program determines the test number and creates a unique test filename with the test number, detector name, and wavelength.

The program moves the detector to the first x and y position and takes the detector to monitor signal ratio measurement (eq (3.23)). The program scans the detector from top to bottom and left to right. That is, the x,y movement is from the top left to the bottom right (or top right depending on the number of columns measured). The program displays a *quasi* three dimensional graph of the signal ratios. The absolute value of the ratio data is plotted in case the polarity of the diode is reversed. This graph is updated after each data point measurement. Also displayed are the current horizontal and vertical positions. The ratio and percent standard deviation data from each x,y position are combined into arrays and added to the output file saved on the hard disk. After the spatial scan is complete a record of the operator inputs and a spatial graph of the signal ratios is printed.

The responsivity spatial uniformity output data file is an ASCII text array that is tab delimited. The file consists of “header” lines and data lines. The “header” lines contain information about the measurement parameters, operator comments, laboratory temperature, humidity, etc., and detector temperature (if provided). The data lines consist of y rows and x columns of the test detector to monitor detector signal ratios. The first data point (array cell) corresponds to the upper left x,y scan position. That is, the array corresponds to looking at the detector where the left side of the array is the left side of the detector, the top of the array is the top of the detector, etc. Following the ratio data array is a similar array containing the corresponding relative standard deviations.

7. Uncertainty Assessment

The assessment of the uncertainties for the detector responsivity measurement is explained in this section. First the uncertainty is evaluated for the measurement equation developed earlier in this document. In addition to the uncertainty terms that come directly from the measurement equation there are indirect terms due to the wavelength uncertainty of the monochromator, long-term stability of the working standards, and the assumptions and approximations made during the development of the measurement equation. Second, the uncertainty for each group of working standards and the transfer to customer detectors is given in detail. The uncertainty analysis follows the method outlined in Ref. [7]. A general discussion of the sources of error in radiometry can be found in Refs. [50 and 51]. A detailed explanation of the evaluation and expression of measurement uncertainty is given in Ref. [52].

7.1 Uncertainty Components

In general, a measurement result y can be expressed as a functional relationship f of N input quantities x_i given by,

$$y = f(x_1, x_2, \dots, x_N). \quad (7.1)$$

The combined standard uncertainty $u_c(y)$ is given by the law of propagation of uncertainty as the following sum,